Study of the dark current in a spectrograph with a CCD camera

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***Abstract*-- The spectral analysis of radiant quantities is usually performed using spectrographs with a CCD camera attached. The pixels of the CCD camera employ the photoelectric effect to generate electrical signals which are proportional to the intensity of light received. However, as a number of electrons will be generated even in the darkness, a "dark current" will be recorded too which adds to the measurement of the signal of the light source being analyzed.**

In this work we present the study of the dark current of a spectrograph (Oriel Instruments, model 74055) with a CCD camera (Andor Technology, DB420-OE model, silicon based) attached. Values between 2 and 40 seconds were considered for the integration time. Detector temperature was varied between 238 and 288K. Data processing led to two mathematical models corresponding to the dependence of the dark current with the integration time and the temperature of the detector, respectively.

***Index Terms*—CCD, dark current, integration time, sensor temperature.**

I. Introduction

THE spectral analysis of radiant quantities is usually performed using spectrographs with a Charge Coupled Device (CCD) camera attached.

A spectrograph is an instrument which has a prism or a grating built in as dispersive element. The optical design is such that the selected wavelengths are always leaving the instrument in the same direction. Behind the wide opening of the spectrograph´s exit plane, an array detector is mounted. A CCD camera is a solid-state image sensor, covered by an array of light sensitive elements called pixels [1]. Each pixel employs the photoelectric effect to generate electrical signals which are proportional to the intensity of light received. Each pixel gathers the generated electrons during a certain integration time, which can be selected according to the signal intensity and the capacity of the pixel. High sensitivity and long integration times are to be used when weak light sources have to be detected.

However, a number of electrons may be generated within the CCD camera even in the darkness (that is, not by the absorption of photons), giving rise to a "dark current" which arises from a physical processes within the CCD itself. These electrons are thermally emitted within the semiconductor lattice comprising the CCD, and add to the measurement of the signal of the light source being analyzed. There are three main sources of dark current [3]: i) thermal generation in the depletion region, ii) thermal generation and diffusion in the neutral bulk material, and iii) thermal generation due to surface states, being the last one the responsible for the generation of the majority of the electrons. As the dark current depends strongly on the detector temperature, it can be made negligible with sufficient cooling.

Dark current is not noise; it's an unwanted signal which should be taking into account when measuring. Like any signal, dark current has a statistical fluctuation known as "dark current noise". A study of the dark current for a particular spectrograph-CCD camera system was performed.

II. Materials and Methods

An Oriel Instruments 74055 MS260i spectrograph [4] and an Andor DB420-OE CCD detector [5] (silicon based) were used, controlled by LabVIEW 7.0 which allow control the integration time of the signal (in this case the dark current) and the temperature of the CCD camera sensor (figures 1 and 2).

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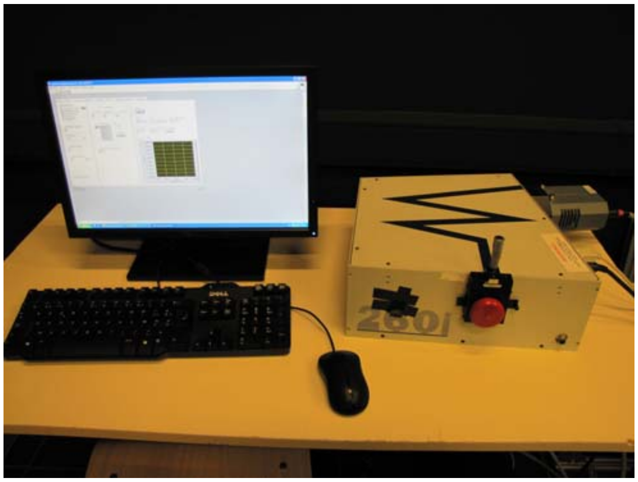

Fig. 1- Experimental setup for dark current measurements.

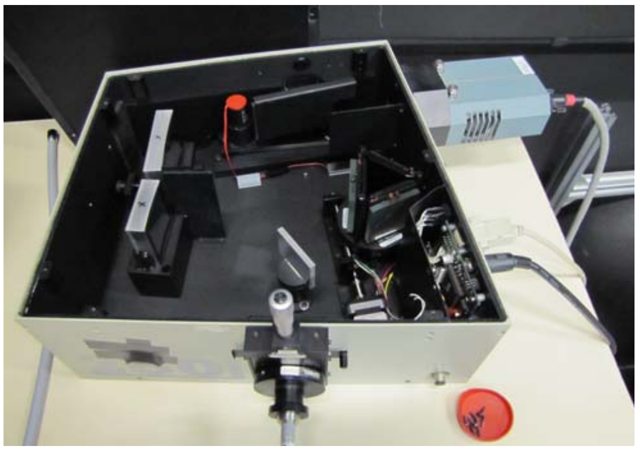

Fig. 2- Internal view of Oriel Instruments 74055 MS260i spectrograph, with the CCD camera attached.

The dark current behavior was studied by measuring the number of accounts M registered in each pixel of the CCD, since both quantities are directly proportional to each other.

All the measurements were carried out in a dark room.

The dependence of the dark current with each pixel was experimentally controlled for the minimum and maximum values of integration time and temperature. The measurement of each point was repeated 25 times.

The dependence of the dark current with the integration time and the sensor temperature was experimentally studied. The control for the integration time was performed for 2, 5, 10, 15, 20, 25, 30, 35 and 40 seconds. The control for the CCD temperature was performed for 238, 243, 248, 253, 258, 263, 268, 273, 278, 283 and 288K. The measurement of all points was repeated 25 times.

III. RESULTS AND DISCUSSION

A. Influence (on the signal) of the light emitted by the monitor

By making this control, results as those shown in Figure 3 as an example were obtained.

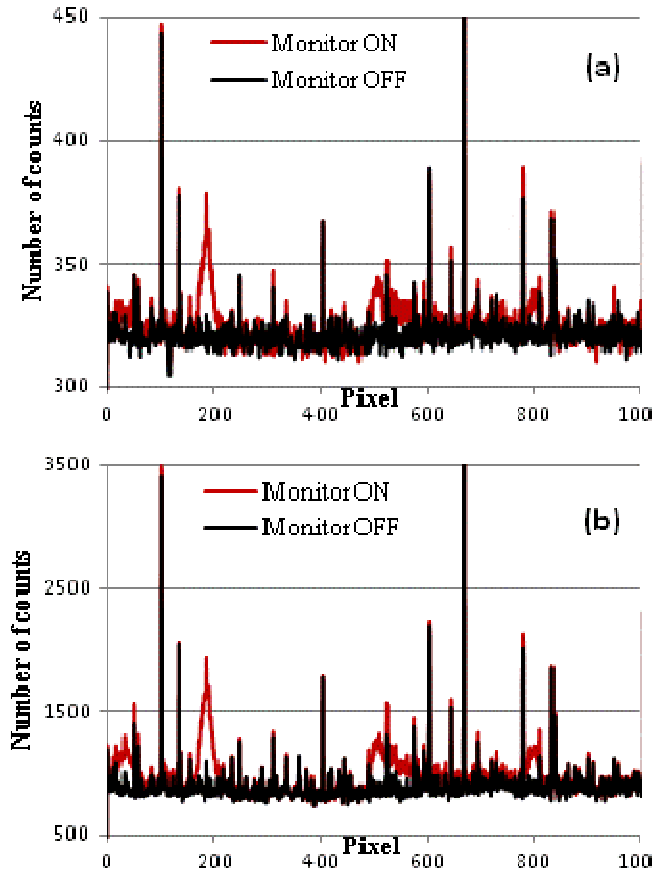

Fig. 3- Signals measured at 243K by the spectrograph with the PC monitor on and off, for (a) 2 and (b) 40 s integration time.

The peaks observed in the graphs corresponding to the measurements with monitor on, bring out that the light from the PC monitor, however tenuous, significantly affects the measurements made by the spectrograph. With this result in mind, all the subsequent measurements were made making sure that the light from the monitor didn't reach the spectrograph shutter.

B. Dependence of the dark current with the pixel

By making this control, results as those shown in Figure 4 as an example were obtained.

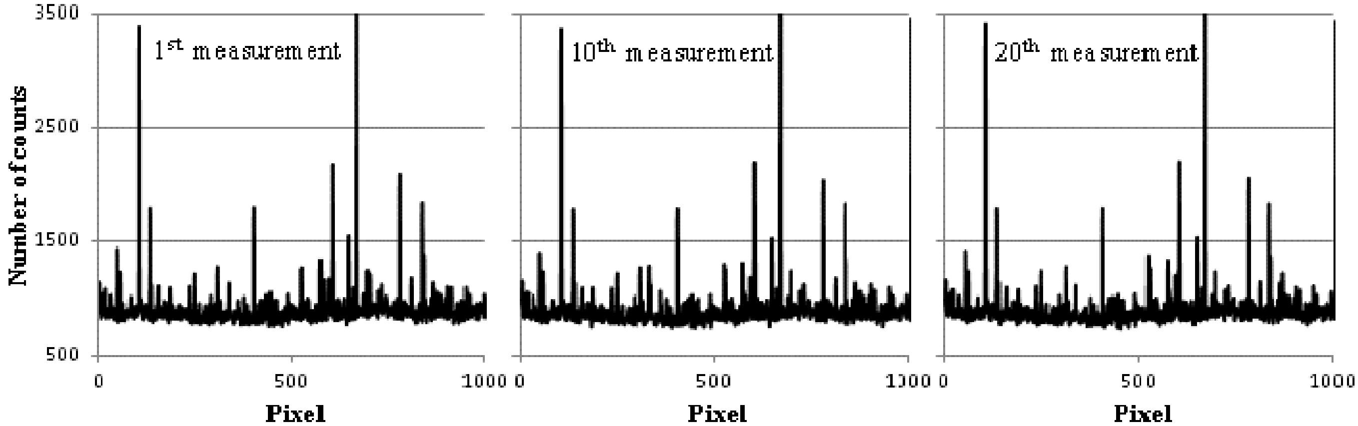

Fig. 4- Signals obtained by repeating the measurement of M for given values of integration time and sensor temperature (in this case 40s and 243K).

It is noted that the dark current signal is affected not only by the dark current noise (random fluctuations) but also by peaks that occur repeatedly in the same pixels when the measurement is performed under the same conditions. These peaks may be due to the introduction of defects or impurities [2] on the lattice of the sensor semiconductor, which generate interface states in the forbidden energy gap between the valence and conduction bands.

As in this study we are concerned with the overall sensor response to integration time and sensor temperature, an average of the Mi values of dark current obtained for each pixel was calculated for each time and temperature. Thus an average value of <M> was obtained, which was associated to the complete sensor for such values of time and temperature.

It was found that the dispersions associated to the dark current mean value were very small compared to the measured quantities, for all points. Their values ranged between 0,11 and 6,34 number of counts, except for one point (t = 30 s, T = 273 K) which presented a deviation of 17,99 for an average value <M> = 25776,56 number of counts. No regular dependence of the standard deviations neither with the integration time nor the temperature was detected.

C. Dependence, with the integration time, of the dark current associated to the CCD

By making this control, the results shown in Figure 5 were obtained.

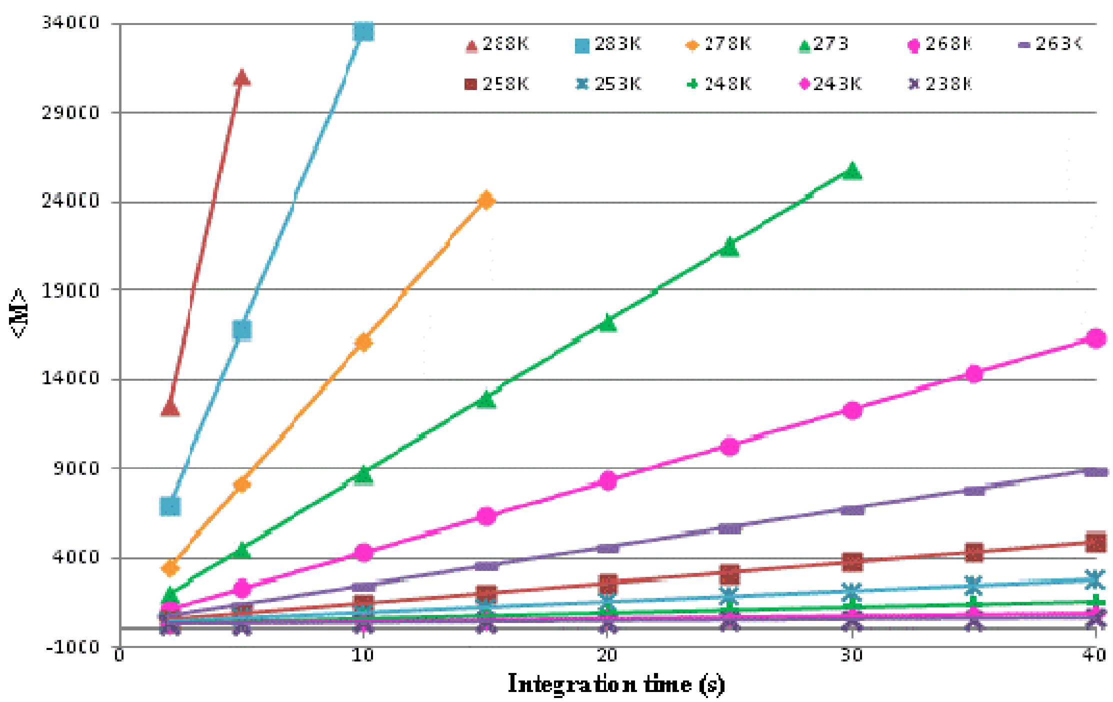

Fig. 5- Mean value of number of counts <M> vs integration time, for different CCD temperatures.

It can be seen that dark current linearly increases with exposure time, according with results reported by other researchers [6].

The very regular behaviour observed in figure 1.5 allowed the development of a mathematical model corresponding to the dependence of the dark current with the integration time.

The relationship between the mean value of the number of counts and the integration time may be represented by the following linear equation:

$$\langle M \rangle = M_0(T) + a(T) \cdot t \tag{1}$$

The dependence of the parameters M_0 and *a* with the CCD temperature was controlled. In figures 6 and 7 the obtained results can be seen.

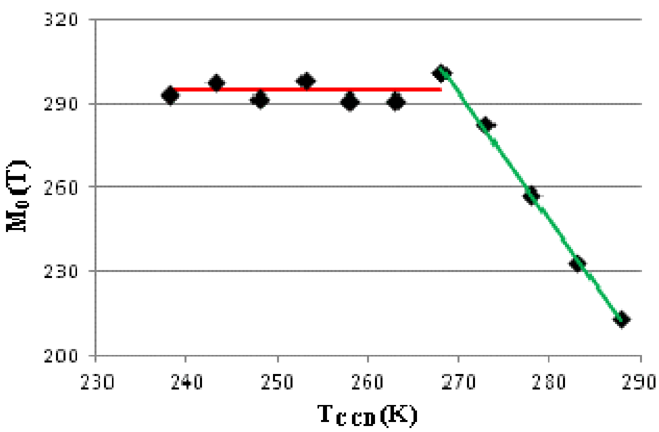

Fig. 6- Dependence of M_0 with the CCD temperature.

From figure 6 it can be noted that the influence of the CCD temperature on the starting value of the dark current (called read-out noise) becomes significant for temperatures higher than a certain critical value, equal to approximately 268K for this setup. The horizontal adjustment was performed by imposing to M_0 a constant value, equal to the average of the values corresponding to the points measured between 238 and 268 K. This procedure is justified by the fact that the standard deviation of these seven points is equal to 4,08 number of counts, value which is in the range of variation of the standard deviations of <M> for the points measured 25 times.

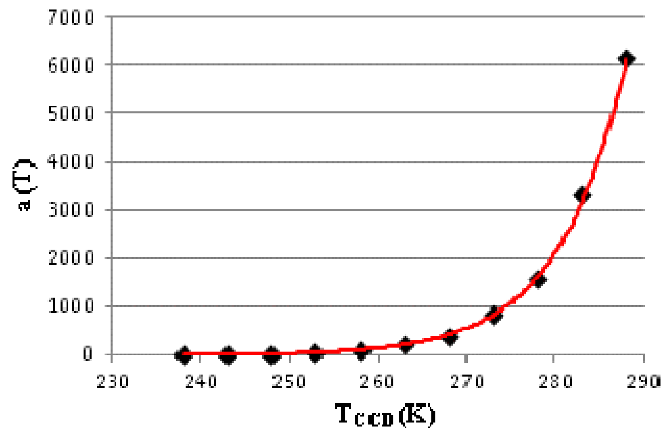

Fig. 7- Dependence of *a* with the CCD temperature.

In figure 7 it is shown that when the CCD temperature increases, the rate of change of dark current also increases, with an exponential behaviour.

D. Dependence, with the sensor temperature, of the dark current associated to the CCD

By making this control, the results shown in Figure 8 were obtained.

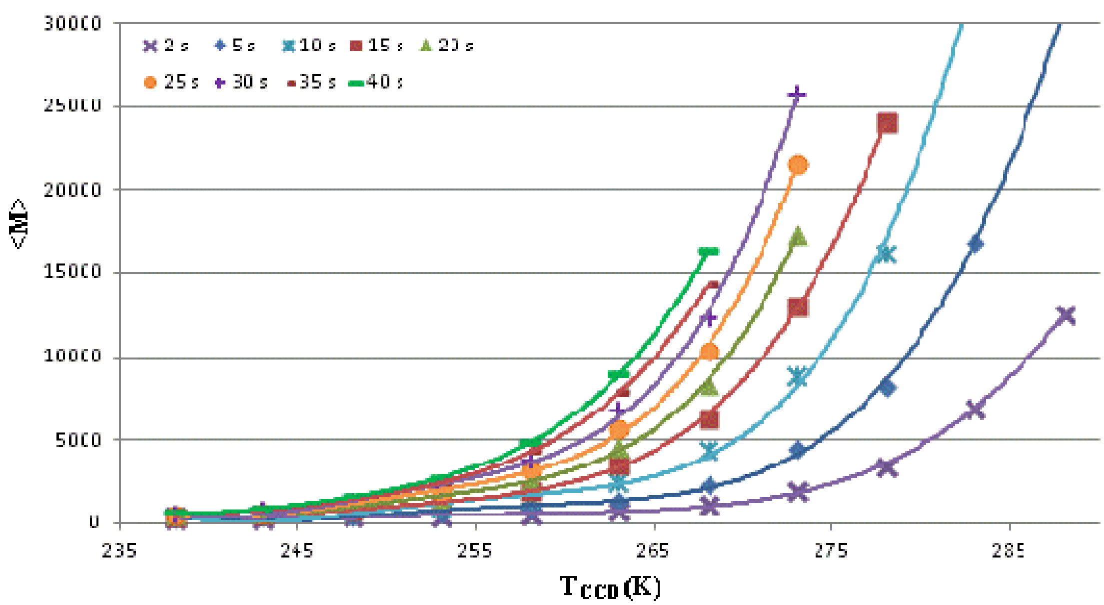

Fig. 8- Mean value of number of counts <M> vs CCD temperature, for different integration times.

The very regular behaviour observed in figure 8 also allowed the development of a mathematical model corresponding to the dependence of the dark current with the temperature of the detector.

The relationship between the mean value of the number of counts and the CCD temperature may be represented by the following polynomial equation:

$$\langle M\rangle = b(t)\cdot T^4 + c(t)\cdot T^3 + d(t)\cdot T^2 + e(t)\cdot T + f(t) \quad (2)$$

The dependence of the five parameters b, c, d, e and f with the integration time was controlled. In figure 9 the obtained results can be seen.

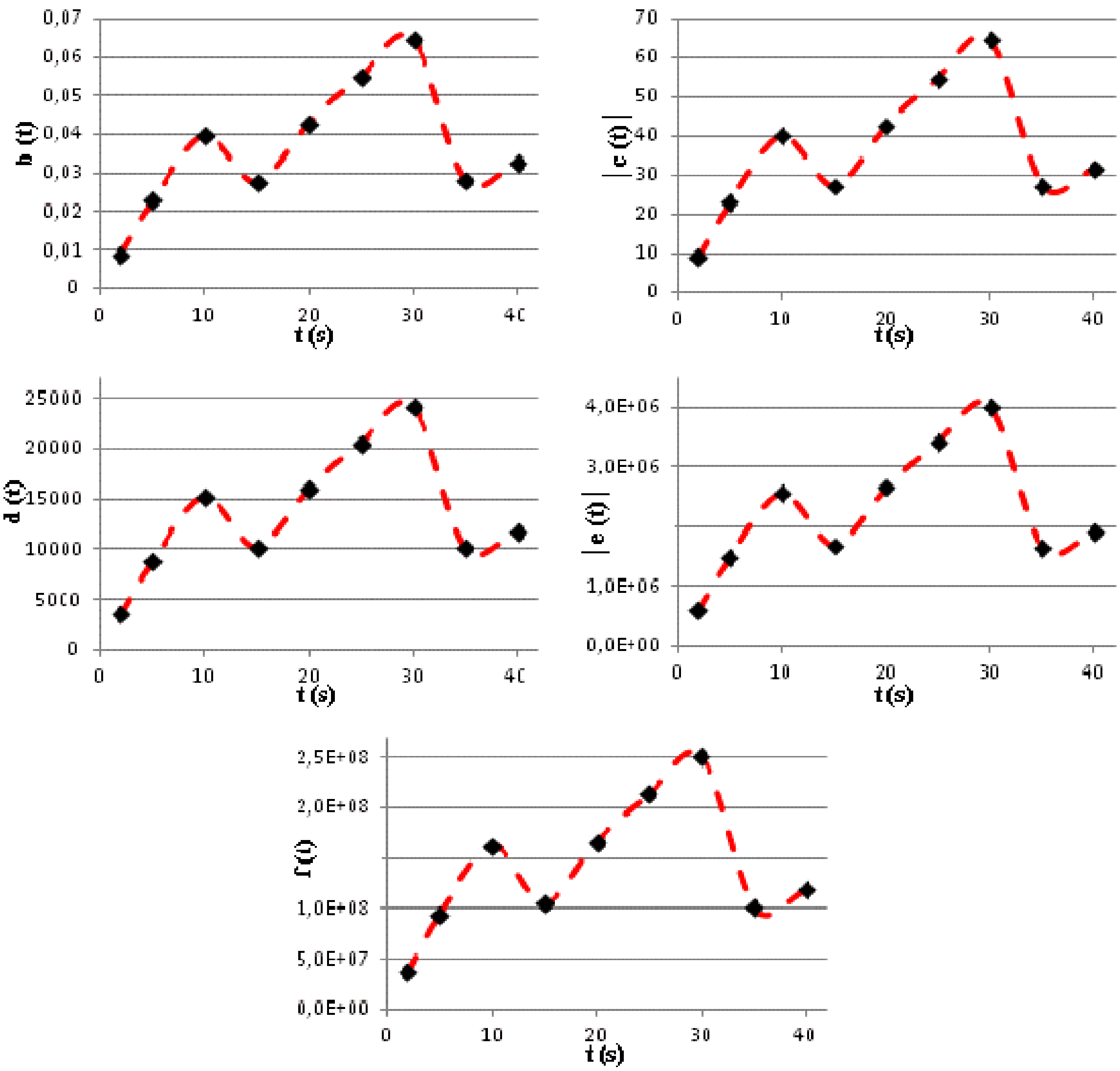

Fig. 9- Dependence of the five polynomial parameters with the integration time.

It is observed that all the parameters have non-monotonic behaviour, with increases and decreases as the integration time rises. It is remarkable the outstanding similarity of the graphs obtained for the five parameters, which suggests that all of them might be modulated by the same dependent-on-integration time function, affected in each case by a different constant of proportionality (for the setting of the corresponding unit and scale of values).

Accordingly, equation (2) may be written as:

$$\langle M\rangle = F(t)\cdot\left[b\cdot T^4 + c\cdot T^3 + d\cdot T^2 + e\cdot T + f\right] \quad (3)$$

IV. CONCLUSIONS

A study of the dependence of the dark current with the integration time and the CCD temperature was performed. The measurements were carried out under normal experimental conditions (with the shutter of the spectrograph closed).

A preliminary study on the influence of the monitor light on the measured signal being measured was performed. It was found that the monitor light significantly affects the measured dark current.

Another preliminary study, in this case on the signal variation with the CCD pixel, was also performed. It was found that all pixels do not respond in the same way when submitted to the same conditions (there are different behaviors that might be associated with defects or impurities in the crystal lattice of the sensor).

Data processing led to two mathematical models corresponding to the dependence of the dark current with the integration time and the temperature of the detector, respectively.

A linear relationship was obtained by studying the dependence of the dark current with time integration. The influence of the CCD temperature on the starting value of the dark current becomes significant for temperatures higher than a certain critical value. When the CCD temperature increases, the rate of change of dark current also increases, with an exponential behaviour.

A polynomial relationship was obtained by studying the dependence of the dark current with sensor temperature. All the parameters of this relationship seem to be modulated by the same dependent-on-integration time function, affected in each case by a different constant of proportionality. Deepening the study of the time integration dependence of these parameters and looking for possible physical interpretations of these results, would be interesting.

V. REFERENCES

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VI. BIOGRAPHIES

Claudia Beatriz Sandoval Salinas (1984) received her B. S. degree in Physics at the National University of Tucuman (Argentina). She is currently beneficiary of a doctoral fellowship from CONICET and she is currently pursuing a Ph.D. degree in Visual Environment and Efficient Lighting at the same University. Her research interest includes spectral radiometric and photometric characterization of light sources and materials, as well as museum lighting. She is member of AFA (the Argentinian Society of Physicists), the OSA Tucuman Chapter and the SPIE Tucuman Chapter.

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Elisa Margarita Colombo (1951) graduated from the National University of Tucuman (Argentina) as Physicist and in the same university; she obtained her PhD being her special field of interest the influence of the lighting on functional vision. Her Posdoctoral Fellowsheep was done in the University of NewCastle upon Tyne where she worked with Dr. Andrew Derrington training on visual psychophysics, and also with Dr. Pablo Artal (Murcia, España) training on visual optics. Head of the Institute of Research on Light, Environmet and Vision. Vice Director of CONICET Tucumán. Member of ICVS (International Colour Vision Society), AFA (the Argentinian Society of Physicists), AIVO (the Argentinian Society on Vision and Ophthalmology), AADL (the Argentinian Association on Lighting). She is the reference member of the Chapter OSA (Tucuman).

José Domingo Sandoval (1953) graduated from the National University of Tucuman (Argentina) as Electrician Engineering (Industrial orientation), and in the same university he obtained his Master's degree in Lighting. Professor of "Photometry Laboratory"; "Colorimetry Laboratory"; "Illumination and Photometry"; "Light and Plants" for graduates and undergraduates. Professor and Researcher in the Department of Lighting, Light and Vision (DLLyV, UNT) and Light, Environment, and Vision Research Institute (ILAV, UNT-CONICET). Areas of Interest: Spectroradiometry of light sources and materials; Spectral characterization and colorimetry of solid state light sources; Detectors and radiometric, photometric, and colorimetric instruments; Lighting for museums and art galleries; Interaction of radiation and matter; Radiation effects in artworks, plants, animals; Deterioration; Spectral signatures; Remote Sensing of agronomic problems.

Peter Hanselaer (1959) received his PhD in Physics at the University of Gent (B) in 1986. Peter is professor at the KU Leuven, dept. ESAT. In 1997, he founded the Light&Lighting Laboratory which was supported by IWT Flanders and several industrial and scientific partners. Actually, the Laboratory is hosting 20 people. Scientific PhD research activities are combined with consultancy activities towards the industry The main research areas are spectral radiometric and photometric characterization of light sources (flux, colour temperature, . . .) and materials (reflectance, scattering, fluorescence), the development of LED and OLED applications, optical design of secondary optics, energy efficient lighting and visual perception measurements. Peter is also board member of the Belgian Institute on Illumination and Belgian delegate in the CIE, division1.